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Tunable Decoupling and Matching Network for Diversity Enhancement of Closely Spaced Antennas

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***Abstract*— A tunable decoupling and matching network (DMN) for a closely spaced two-element antenna array is presented. The DMN achieves perfect matching for the eigenmodes of the array and thus simultaneously isolates and matches the system ports while keeping the circuit small. Arrays of closely spaced wire and microstrip monopole pairs are used to demonstrate the proposed DMN. It is found that monopoles with different lengths can be used for the design frequency by using this DMN, which increases the design flexibility. This property also enables frequency tuning using the DMN only without having to change the length of the antennas. The proposed DMN uses only one varactor to achieve a tuning range of 18.8% with both return loss and isolation better than 10-dB when the spacing between the antenna is 0.05λ. When the spacing increases to 0.1λ, the simulated tuning range is more than 60%.**

***Index Terms*— Antenna array, compact array, mutual coupling, antenna decoupling, antenna diversity, MIMO.**

I. Introduction

Multiple-input-multiple-output (MIMO) systems, which usually require a larger area for the antennas and their associated networks, can improve system performance compared to single-input-single-output (SISO) systems. However, when miniaturizing the MIMO antenna system, the mutual coupling between the antennas inevitably becomes stronger and the radiation efficiency and diversity of the antennas are affected.

There are two techniques to improve the radiation efficiency when strong mutual coupling is present. The first technique employs a corporate feed to cancel the reflection coefficient of a single antenna and the mutual coupling [1]. The second technique uses matching networks to match the mode impedances which are also known as the eigenvalues of the compact array [2]. The first technique requires the specific design of the spacing between the antenna array elements. The second technique is more adaptable for different antennas and spacings. Since the ports are isolated, the diversity of the antenna system is improved [3], [4].

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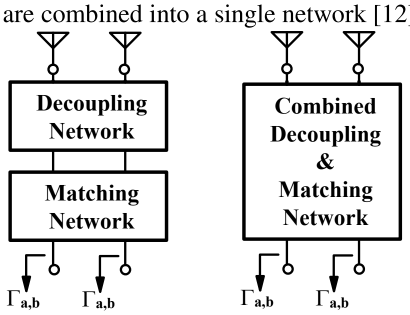
Two methods are commonly used in the design of DMNs. In the first method, the ports are isolated from each other using the inherent characteristics of couplers [5]-[9] and then matched. In the second method, the reflection coefficients of different eigenmodes are canceled using networks of reactive components [10]-[15]. The first method assigns the individual eigenmodes to different ports, which causes the bandwidths of the ports to differ from each other. The couplers have low loss, but occupy a large area. The second method considers all the eigenmodes so that all ports have a similar bandwidth, and the realization is compact. Both methods yield narrow bandwidth due to the inherent high quality factors of some of the eigenmodes. The bandwidth is related to the type of elements and the element spacing. For example, the 10-dB return loss bandwidth of a two-element array with spacing of 0.1λ on a small metal ground plane is typically less than 2% [6], while the bandwidth of two printed monopoles on a substrate is typically around 4% [10]. It is desired to make the center frequencies tunable [16]. Recently, reconfigurable DMN for closely space antennas were reported, more than one varactor/switch were used [17], [18].

In this paper, a compact DMN with frequency tuning capability using a single varactor is proposed. To minimize the number of components, the proposed DMN decouples and matches the ports simultaneously. More importantly, the center frequency is mainly determined by one design parameter of the DMN, and therefore the frequency of the array can be made tunable without changing the characteristics of the elements (e.g. the dipole length). As a proof of concept, two antennas on a substrate with a spacing of 0.05λ and a tunable DMN are designed and measured. The measured bandwidth is more than 2.5%, and the frequency tuning range is 18%.

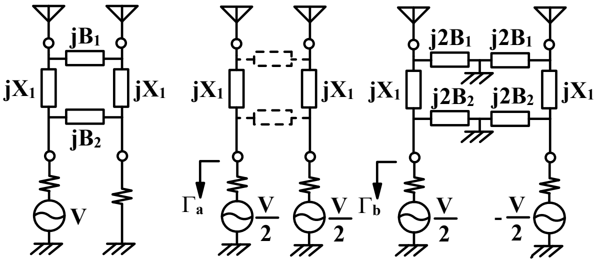
II. Proposed Compact DMN Design

Fig. 1(a) shows the DMN that separately decouples and matches the two ports. Various networks can be used in the design of this network [5]-[11], [13]-[16]. Fig. 1(b) shows the concept of DMN where decoupling network and matching network are combined into a single network [12], [19]. The



(a) (b)

Fig. 1. (a) DMN with separate decoupling and matching, (b) DMN with combined decoupling and matching.



(a) (b) (c)

Fig. 2. (a) Proposed DMN, (b) mode *a* (even-mode), (c) mode *b* (odd-mode).

proposed DMN is shown in Fig. 2(a), which contains fewer components compared to the separated decoupling and matching networks. The modal impedances of a given array are found from the eigenvalues of the impedance matrix [2]. In the case of two antennas, the eigenvectors are given by $\mathbf{e}_a=[1, 1]^T$ (even mode) and $\mathbf{e}_b=[1, -1]^T$ (odd mode). The corresponding modal impedances are $Z_a=Z_{11}+Z_{12}$ and $Z_b=Z_{11}-Z_{12}$, from which the reflection coefficients Γ_a and Γ_b can be obtained as shown in Fig. 2. When $\Gamma_a=\Gamma_b$, the even-mode and odd-mode powers at port 2 have the same magnitude but opposite direction, so that the ports are isolated. When the same network is used for port matching, $\Gamma_a=-\Gamma_b$. The network should thus be designed to have the two modes self-matched, i.e. $\Gamma_a=\Gamma_b=0$. To achieve this requirement, the characteristics of the elements need to be carefully adjusted before being decoupled and matched by the DMN. The design procedure is as follows:

1. To match the even-mode in Fig. 2.(b), the elements are designed such that:

$$\mathrm{Re}\left(Z_{11}+Z_{12}\right)=Z_0 \tag{1}$$

where Z_0 is the chosen system impedance. When monopoles are used, the self impedance and mutual impedance in (1) are mainly determined by the length of the antenna when the spacing is fixed. If (1) is not satisfied, a transmission line or a shunt admittance can be used to rotate the reflection coefficient to the $R=Z_0$ circle in the Smith Chart.

2. X_1 is then chosen so that the even-mode is matched, i.e.

$$X_1=-\mathrm{Im}\left(Z_{11}+Z_{12}\right) \tag{2}$$

3. To match the odd-mode, B_1 and B_2 are determined by

$$B_1=\frac{1\pm\sqrt{Z_0G_b-X_1^2G_b^2}}{2X_1}-\frac{B_b}{2} \tag{3}$$

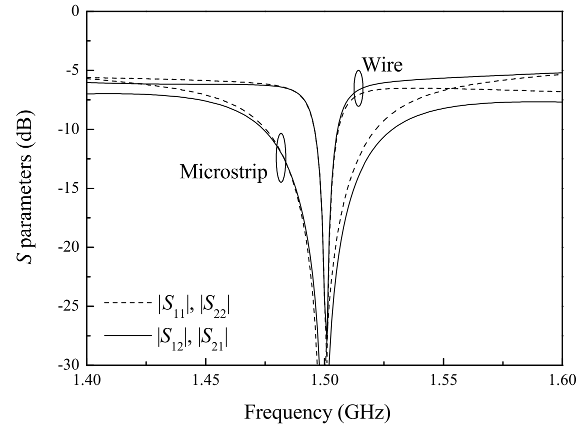


Fig. 3. Performance with DMNs for wire and microstrip monopoles.

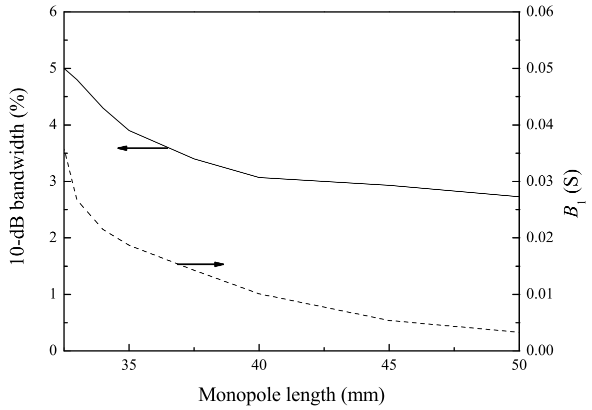


Fig. 4. 10-dB bandwidth versus different antenna length for microstrip monopoles.

$$B_2=-\frac{\left(B_b+2B_1\right)\left[1-X_1\left(B_b+2B_1\right)\right]-X_1G_b^2}{2\left[1-X_1\left(B_b+2B_1\right)\right]^2+2X_1^2G_b^2} \tag{4}$$

where $G_b=\mathrm{Re}(1/Z_b)$ and $B_b=\mathrm{Im}(1/Z_b)$. If the susceptances B_1, and B_2 are not realizable, the designer should go back to step 1 and adjust the antenna parameters and/or the matching network. Fig. 3 shows two examples for the wire and microstrip monopoles [15] with a spacing of 10 mm (0.05λ) and length of 40 mm for a design centered at 1.5 GHz. For ease of comparison, the bandwidth is defined as the intersection of a return loss and an isolation of 10 dB. It is found that the microstrip monopoles have a larger bandwidth (~3%) compared to the wire monopoles (~0.6%). For a range of microstrip monopole lengths, the 10-dB bandwidth and the corresponding value of B_1 are shown in Fig. 4. The bandwidth percentage is with reference to the tuned center frequency, and B_1 is responsible for frequency tuning, and will be discussed in the next section.

III. Frequency Tuning of Proposed DMN

One problem of the mode-based decoupling of closely spaced array elements is the resulting narrow bandwidth. In a two-antenna system, the reflection coefficient Γ_b is the main limitation for both return loss and isolation. The inherent high quality factor of mode b, which is determined by the spacing of the elements, reduces the bandwidth of Γ_b. A reduction in the element spacing causes a decrease in bandwidth. Fig. 5 shows the reflection coefficients $|\Gamma_a|$ and $|\Gamma_b|$ as well as the return loss and isolation of the array for microstrip monopoles with a length of 33 mm and the spacing is 10 mm (0.05λ). As expected (refer to Fig. 4), a slightly larger bandwidth is achieved compared to Fig. 3, where the monopole length is 40 mm. To increase the range of applications, frequency tunability is desired. From Fig. 2, the S parameters of the ports are found as

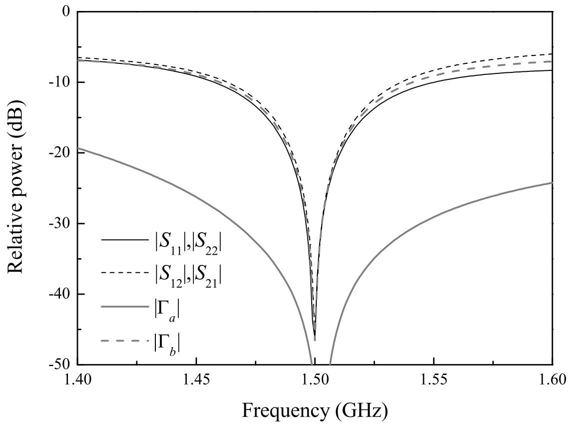


Fig. 5. Reflection coefficients $|\Gamma_a|$ and $|\Gamma_b|$ together with the return loss and isolation of the array for an element spacing of 0.05λ.

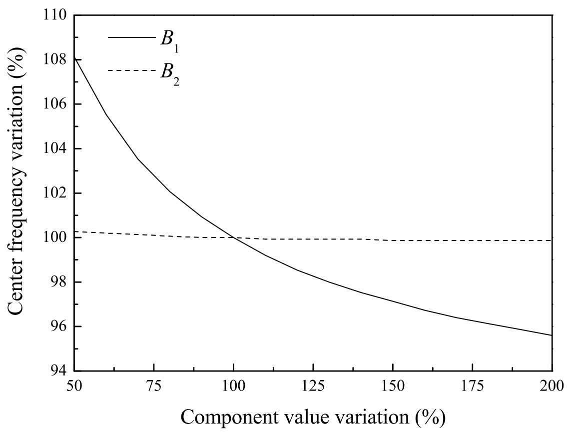


Fig. 6. Relation between the center frequency of $|\Gamma_b|$ and values of B_1 and B_2.

$$S_{11} = S_{22} = 0.5(\Gamma_a + \Gamma_b) \quad (5)$$

$$S_{12} = S_{21} = 0.5(\Gamma_a - \Gamma_b) \quad (6)$$

From Fig. 5, it is observed that mode a contributes little reflected power over a much larger bandwidth compared to mode b. The return loss and isolation are therefore largely determined by Γ_b in (5) and (6). Both the return loss and isolation can therefore be tuned by adjusting Γ_b.

In the conventional approaches where decoupling network and matching network are separated, both networks should be tuned to shift the center frequency of Γ_b. A large number of varactors or switches are required [17], [18]. For coupler-based DMNs, a broadband coupler [20] and a constant 180º phase difference are required [21], which increases the circuit complexity and size. In the proposed tunable DMN, only Γ_b needs to be tuned, while X_1 in Fig. 2 can remain unchanged. The relation between the center frequency of $|\Gamma_b|$ on B_1 and B_2 is depicted in Fig. 6. It is observed that the center frequency of $|\Gamma_b|$ largely depends on B_1. According to Fig. 4, the required susceptance for an element length of 33 mm is B_1=0.0267 S, which is equivalent to a capacitance of C_1=2.83 pF at 1.5 GHz. Fig. 7 shows the frequency response for different values of C_1. When C_1 is varied from 1.1 pF to 5 pF [22], a return loss of 10-dB is achievable over a frequency range of 20%, while a return loss of 15-dB bandwidth is possible over a range of 8%. Note that the antenna spacing is only 0.05λ. According to simulations, the covered bandwidth can be further increased to achieve a 10-dB return loss frequency range of 60% and a 15-dB return loss range of 15% if an element spacing of 0.1λ is used instead. The DMN affects the radiation pattern at each frequency, as described in [15]. However, we have found that the radiation pattern does not change significantly in the frequency range of interest here. The loss in the DMN is most significantly affected by the Q factor of the reactive components. The loss due to the varactor mainly contributes to the loss in the odd-mode. For larger arrays, more varactors would be required [5], [14], [18].

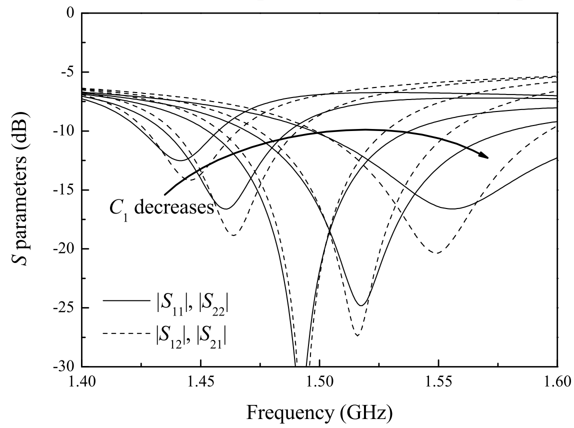


Fig. 7. Frequency tuning achieved by changing the capacitance C_1=B_1/ω for an element spacing of 0.05λ.

IV. Experimental Results

To verify the concept, a tunable two-antenna system with a centre frequency of 1.5 GHz was implemented on FR-4 substrate. Microstrip monopoles were chosen as elements, with a spacing of 10 mm (0.05λ). The ground plane size and element lengths are varied such that (1) is fulfilled. A TRL calibration was used to measure the S parameters of the array, and the measured values were used to design the DMN with the aid of Agilent's Advanced Design System (ADS). The photograph of the fabricated DMN and antennas is shown in Fig. 8. The connection lines were used for impedance transformation so that (1) is satisfied. The length of the connection line was determined by the element spacing and the physical size of the varactor. Then the corresponding components were determined using equations (2)-(4). Murata inductors (Series LQW15 L_1=4.7 nH, L_2=6.2 nH) were used to implement X_1 and B_2, while a Skyworks varactor (SMV1233-079LF) was utilized to provide an adjustable capacitor representing B_1. The varactor has a measured capacitance range from 0.8 pF to 5 pF when the control voltage decreases from 15 V to 0 V. The tunable frequency response is shown in Fig. 9. If larger capacitances were possible, the upper limit could have been extended even further. The achievable frequency range for 10-dB return loss and isolation covers from 1.39 GHz to 1.68 GHz (18.8%), while the corresponding range for 15-dB return loss and isolation was from 1.44 GHz to 1.64 GHz (13%). For each tuning frequency sample, the 10-dB bandwidth is between 2.5% and 5%.

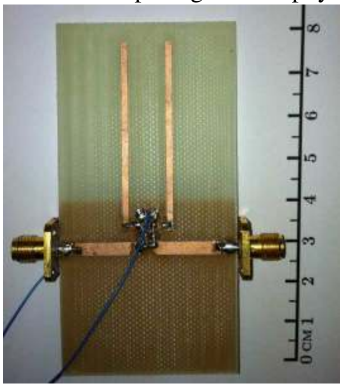


Fig. 8. Photo of the tunable decoupled and matched antenna pair.

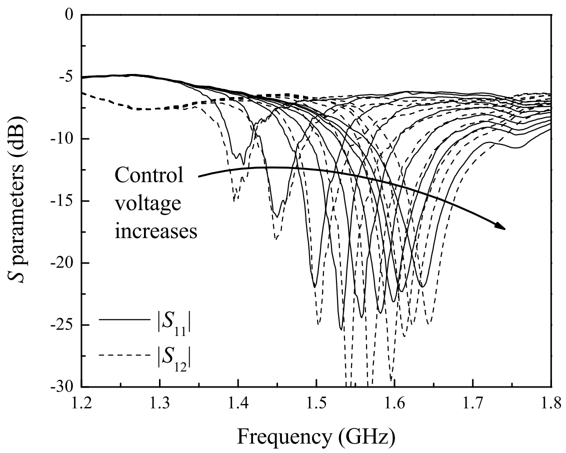


Fig. 9. Measured S parameters of the proposed tunable decoupled and matched antennas.

V. Conclusion

A compact and tunable decoupling and matching network for closely spaced antennas is presented. Both wire and microstrip monopole elements were studied and microstrip monopoles were used to demonstrate the concept. A single varactor is used to tune the matching and the isolation of the ports. The realized 10-dB tuning range is around 18.8% and the 15-dB tuning range is around 13%.

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